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13. ABSTRACT *(Maximum 200 words)*
It is well known that surface tension force dominates the fluid flow in the weld pool (Marangoni effect), influencing weld penetration and properties of the weld. In fact, it has been recently reported by EWI that when a thin surface-active-element-rich layer is coated to the surface of the metal, more than several times of penetration depth was increased for a Gas Tungsten Arc Welding (GTAW) process. The objective of the present study is to systematically study the effects of surface active elements for both GTAW and GMAW (Gas Metal Arc Welding), not only on fluid flow patterns and weld penetration, but also on the distribution of surface active elements in the weld pool and possible formation of defects. Among the many accomplishments achieved by the project, the most significant one is that mathematical models were developed for the first time having the capabilities to simulate the droplet impinging process and the effects of surface active elements for both spot and 3-D moving GMAW. The technologies developed in the present project are being transferred to the General Motors Corporation through a research contract.

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Effects of Surface Active Elements on Pool Convection and Properties of the Welds

Final Progress Report

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by

Hai-Lung Tsai

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University of Missouri-Rolla

TABLE OF CONTENTS

I. Foreword

It has been reported, experimentally and theoretically, that surface tension force dominates the fluid flow in the weld pool (Marangoni convection), affecting weld penetration and properties of the weld. Additions of surface active elements not only can significantly change the magnitude, and even the sign, of the surface tension coefficient (e.g., from negative to positive), but also their amount has deleterious effects on the properties of the weld (e.g., cracking). While the effects of surface active elements have been recognized, the details of the interactions between levels of surface active elements, surface tension, pool convection, and weld penetration are not available and the optimum levels of surface active elements for different welding processes are not known. The objective of the project is to investigate the coupling between the distribution and levels of surface active element, surface tension force, convection, pool shape and penetration, and properties of the weld, under various welding conditions.

II. Statement of the Problem Studied

In this project, the effects of surface active elements were studied for both Gas Tungsten Arc Welding (GTAW) and Gas Metal Arc Welding (GMAW). Several kinds of surface active elements, which can significantly change the surface tension, have been reported (e.g., sulfur, selenium, and oxygen). Generally, surface tension is a complex function of both temperature and concentration of surface active elements. Hence, during welding process, surface tension in the weld pool varies from time to time and from one place to another. In the present study, sulfur is chosen as the surface active element because its surface tension data is easily available. However, the results and conclusions obtained from the present research should be generally true for all surface active elements.

In GTAW, sulfur exists in the original base metal or can be added to the base metal by coating a sulfur-rich layer at the surface. Through shielding gas, sulfur can also be added to the weld pool. In GMAW, sulfur can be added through the electrode containing a higher concentration of sulfur. In the present study, the aforementioned methods of adding sulfur to weld pool were studied. Beginning with when the arc was turned on until the weld pool was completely solidified,

transient temperature, fluid flow velocity, and sulfur concentration distribution in the weld pool were calculated for various welding conditions. Particularly, the emphasis has been placed on how sulfur concentrations affect fluid flow patterns and the resulting weld penetration and possible weld defect formation.

III. Summary of the Most Important Results

1. *Threshold Concentrations of Surface Active Elements for Full Penetration*

Through numerical experimentation, we discovered for given welding conditions, there exists a threshold concentration of sulfur that weld pool abruptly achieves full penetration. For example, as shown in Figure 1, when sulfur concentration is 155 ppm, due to surface tension effects, the fluid flow in the weld pool is complicated and the weld pool is shallow. Points A, B, C, and D in the figure indicate, at different times, the locations at which the maximum surface tension occurs. However, if the sulfur concentration just increases to 160 ppm, a single, clockwise vortex is created to achieve full penetration, Figure 2. The predicted threshold concentration is consistent with the phenomena observed in welding practices. Detailed discussion can be found in Paper [1], Section IV.

2. *A Skewed Weld Pool*

When two metals containing different concentrations of sulfur are welded together, a skewed weld pool is predicted as shown in Figure 3. This is caused by the greater surface tension in the metal containing less sulfur (the left-hand-side metal) so that the fluid at the top of the weld pool is pulled toward the left-hand side. As discussed in detail in Paper [1], Section IV, under an extreme condition, the weld pool can be skewed to nearly only one side of the metal, leading to a poor joint. This is the first time to be able to predict a skewed weld pool by mathematical modeling, although the phenomenon was observed long ago in welding practices.

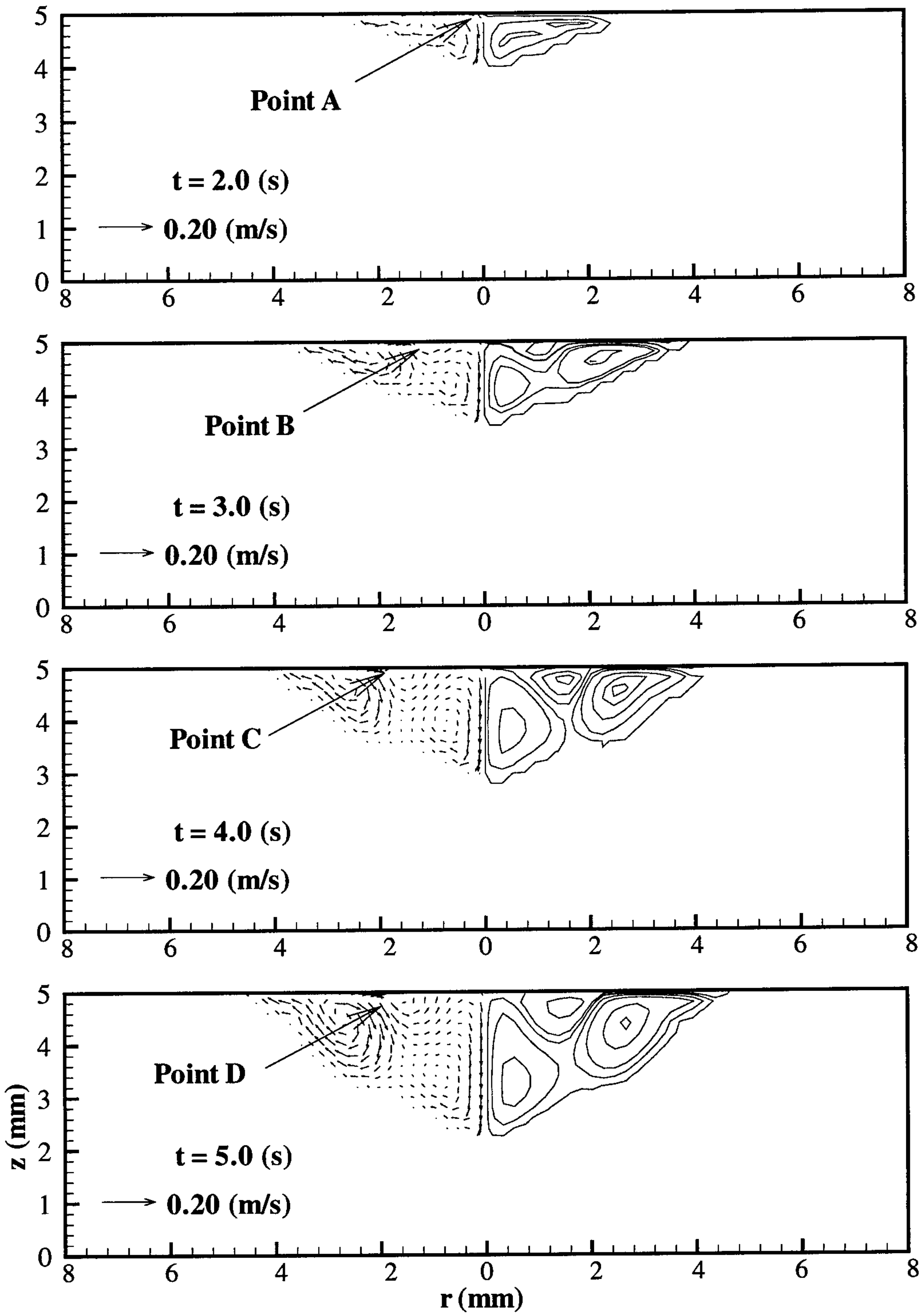

Fig. 1 Velocity vectors and streamline contours at different times; S = 155 ppm.

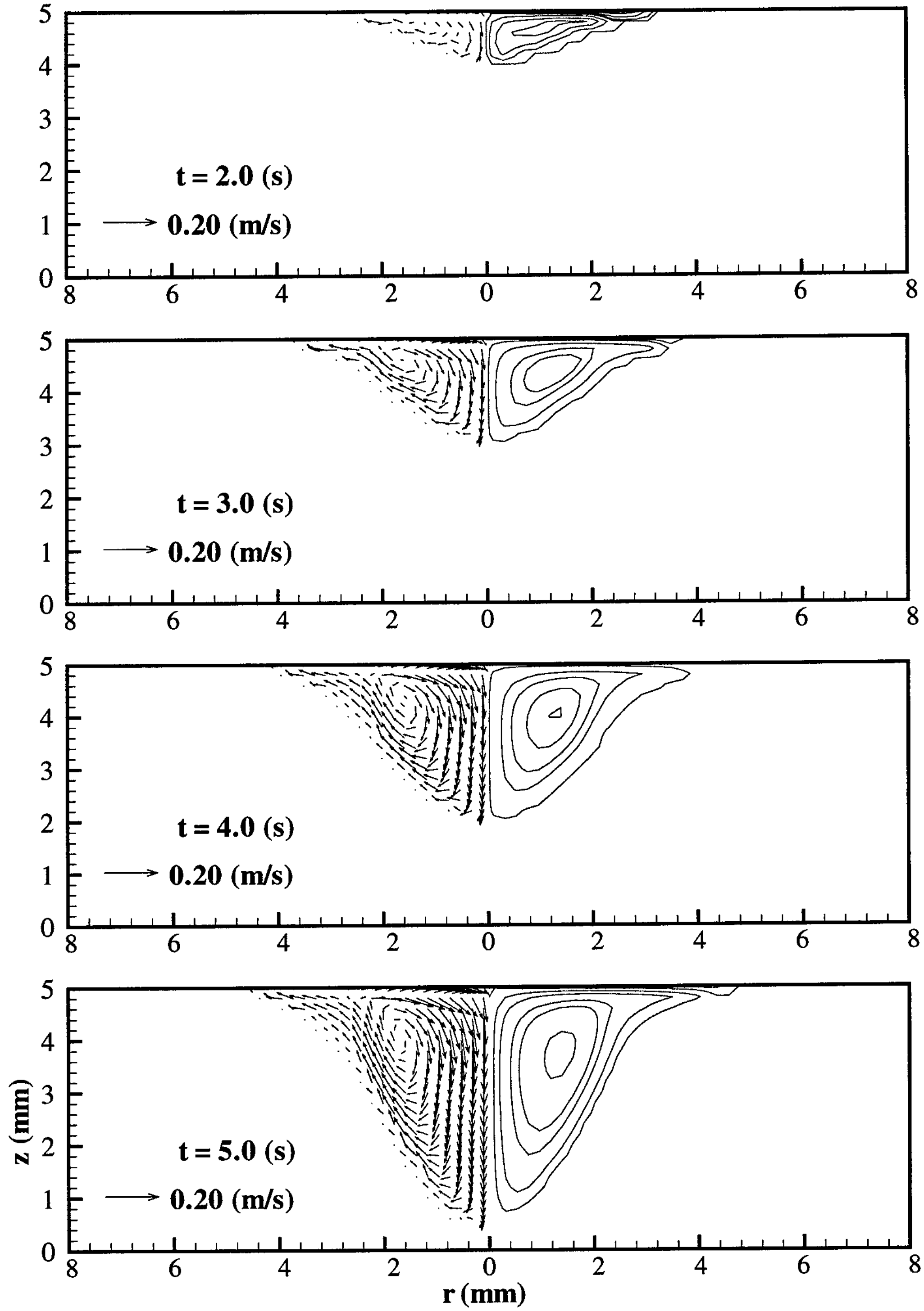

Fig. 2 Velocity vectors and streamline contours at different times; S = 160 ppm.

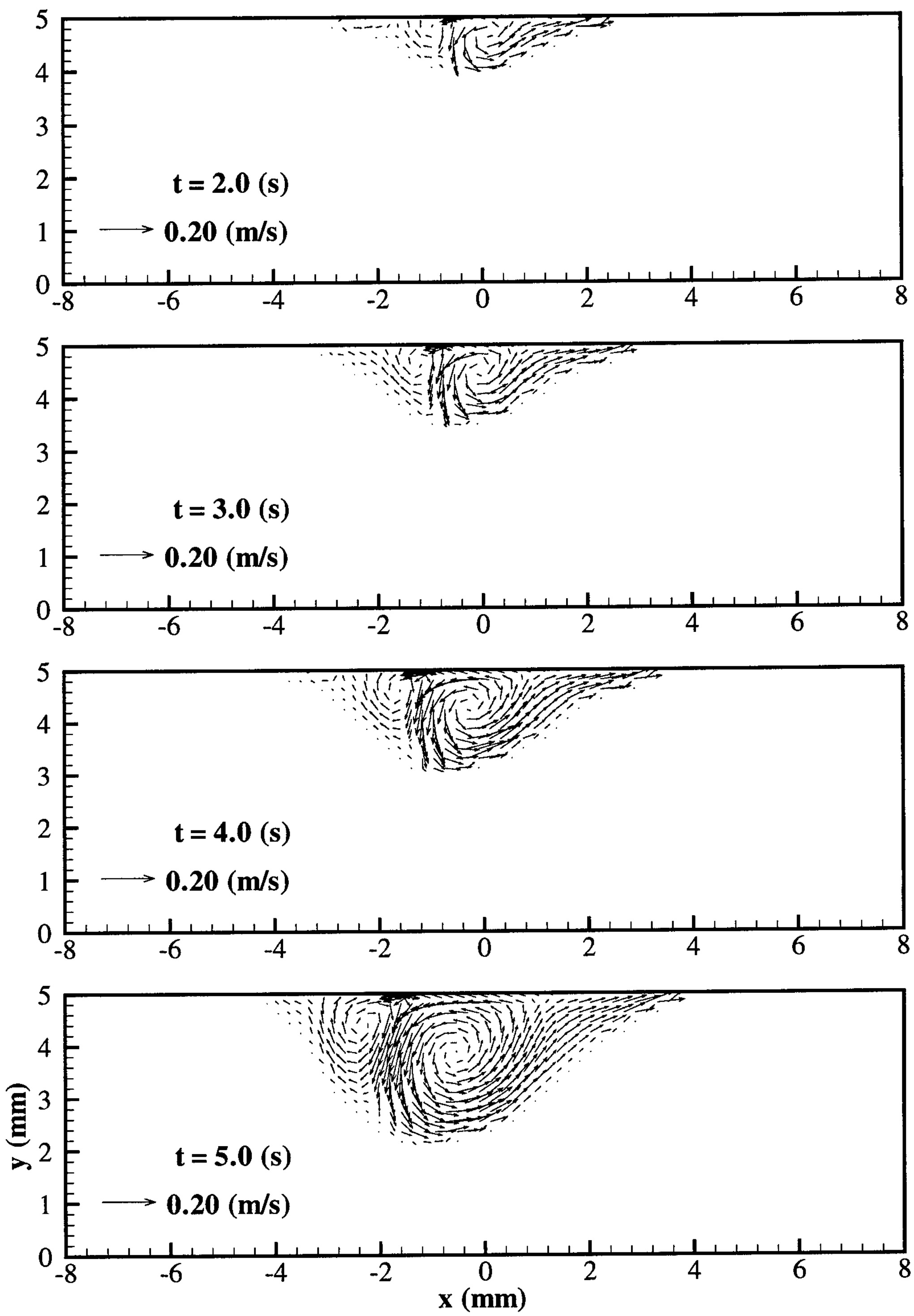

Fig. 3 Velocity vectors at different times when two metals with different sulfur contents are welded together; left-hand-side metal S = 50 ppm, right-hand-side metal S = 200 ppm.

3. *When Coating or Shielding Gas Contains Surface Active Elements*

In addition to the sulfur contained in the base metal, it is also possible to change the sulfur and the surface tension in the weld pool by adding sulfur through a sulfur-rich coating or shielding gas. The weld penetration increases only a little, until the sulfur concentration in the coating (0.2 mm thickness) reaches 900 ppm, a sudden full penetration occurs, Figure 4. Similar phenomena were found when the sulfur concentration in the shielding gas exceeded 1500 ppm, as shown in Figure 5. It is noted that even when a relatively high concentration of sulfur was added, the average sulfur concentration in the weld pool in both Figures 4 and 5 is about normal. Detailed discussion can be found in Paper [2], Section IV.

4. *Coupling of Arc and Weld Pool in GTAW*

In the past, all welding models assumed some sort of arc heat distribution (e.g., Gaussian distribution), and used it as a known input to calculate weld pool temperature and fluid flow. However, a dynamic variation of the weld pool geometry caused by fluid flow can change the arc distribution. In the present study, a complete coupling between the arc and the weld pool dynamics was considered for the first time. Figure 6 shows typical results of arc flow distribution and a fully penetrated weld pool. Detailed discussion can be found in Paper [4], Section IV.

5. *Droplet Impinging Process in GMAW*

It is considered to be the most significant accomplishment in the present research that, for the first time, modeling of the droplet impinging process in GMAW was developed. A sequence of the impinging process is shown in Figure 7. It is seen that the droplet is distorted by the plasma arc drag force and smashed onto the base metal. Figure 8 shows the weld pool dynamics and temperature distribution as a function of time until complete solidification after the last droplet impinges onto the weld pool. Detailed discussion of the mathematical model and numerical techniques can be found in Paper [5], Section IV.

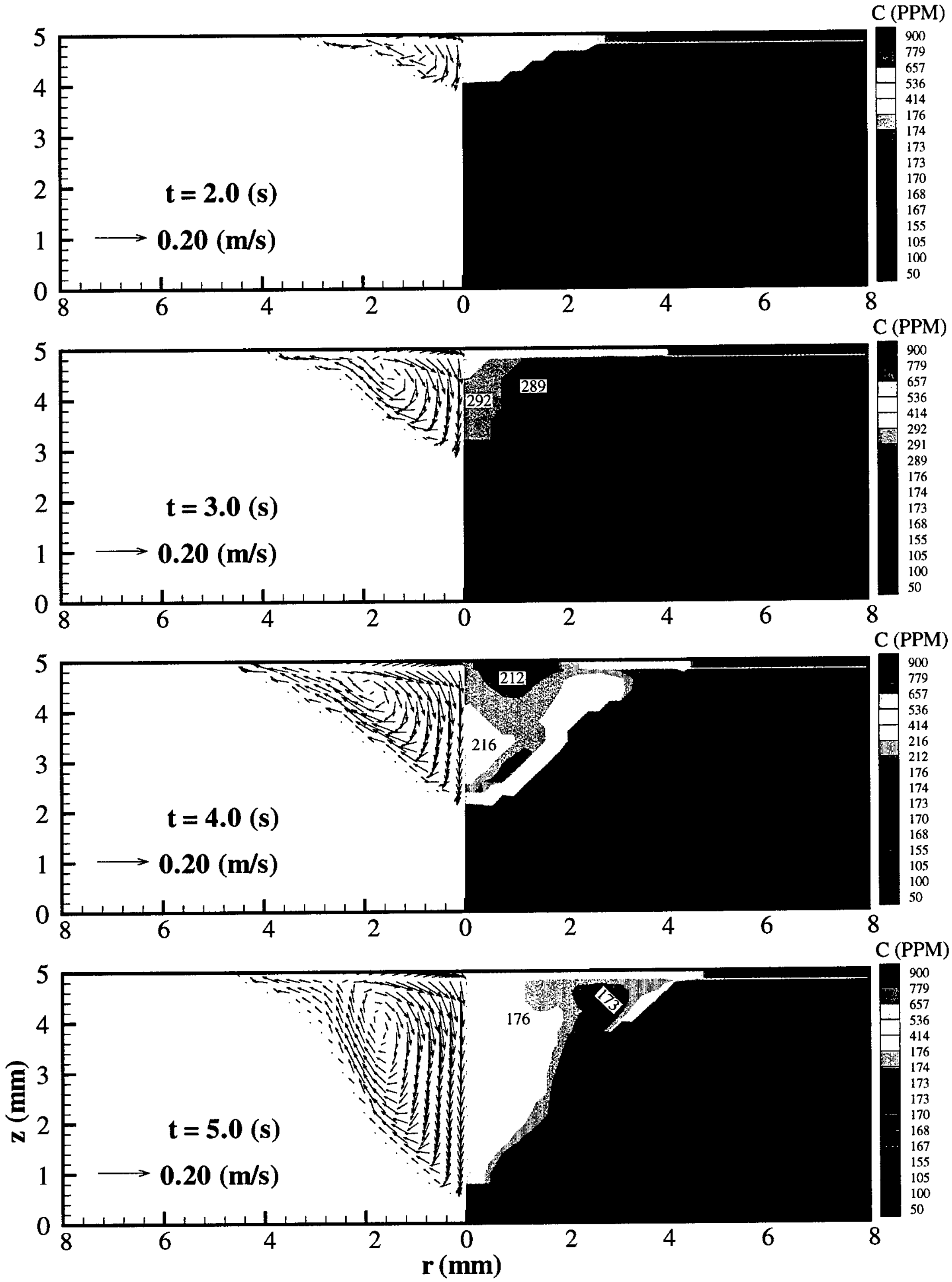

Fig. 4 Velocity vectors and concentration shading at different times; S = 900 ppm, coating thickness is 0.2 mm.

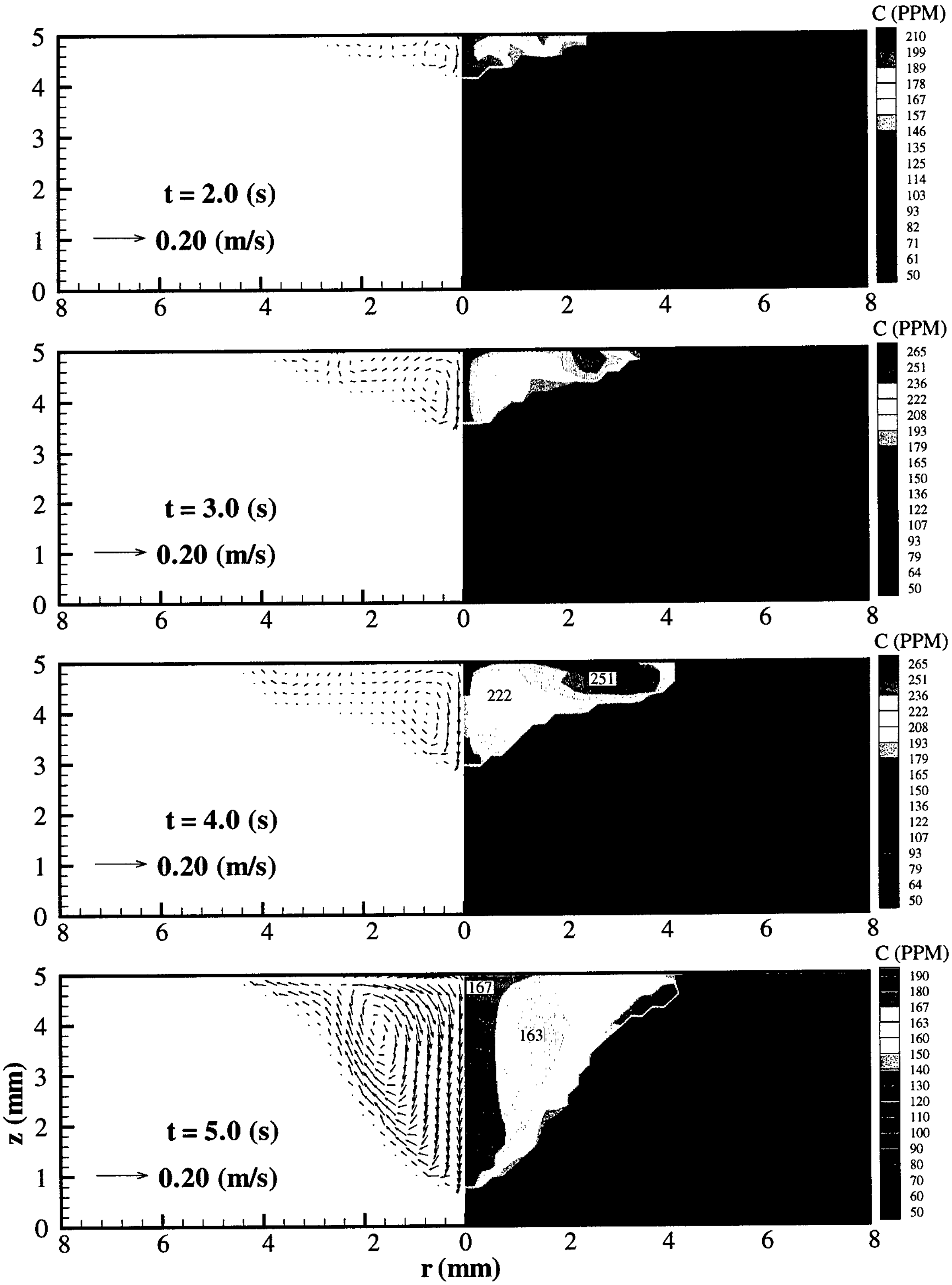

Fig. 5 Velocity vectors and concentration shading at different times; S = 1500 ppm, added through shielding gas.

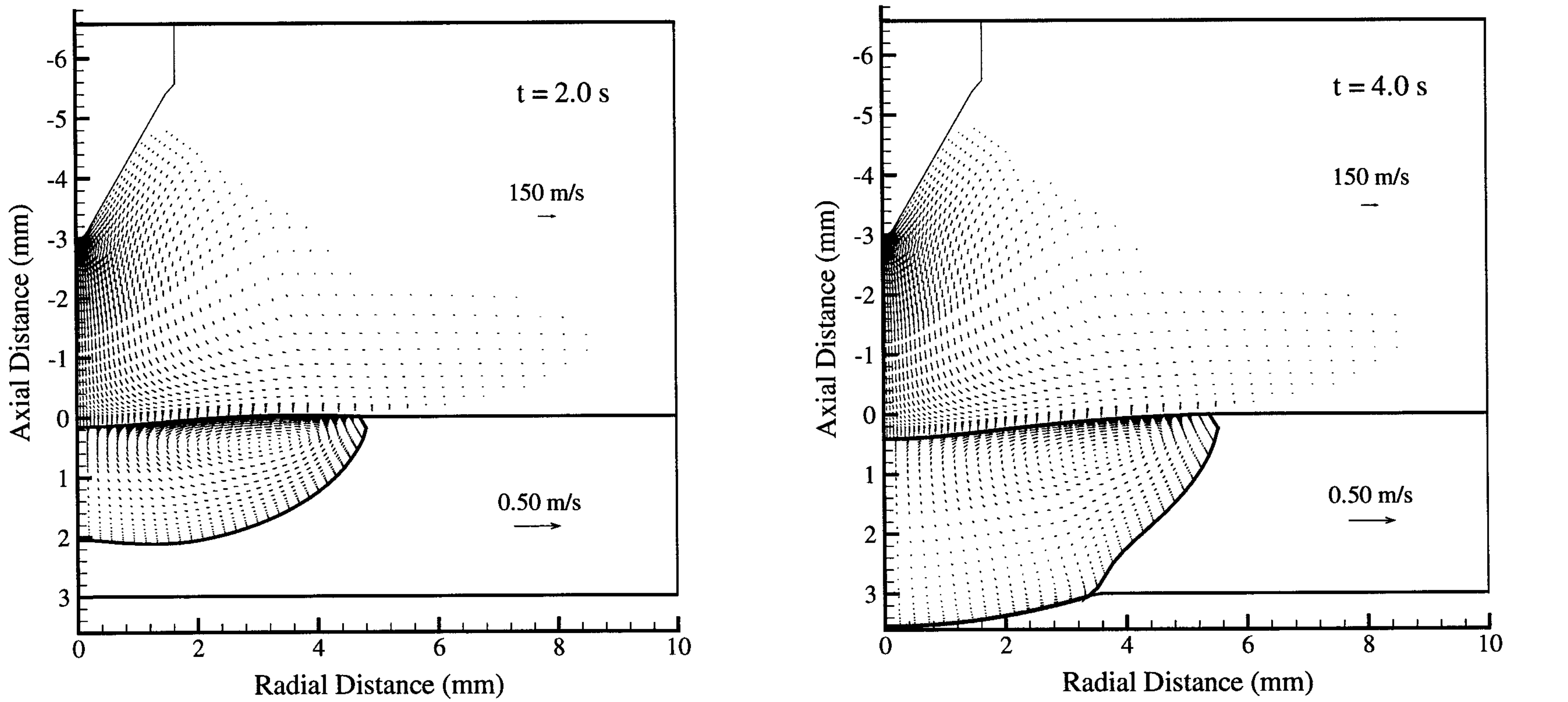

Fig. 6 Fluid flow of both welding arc and molten pool in GTAW.

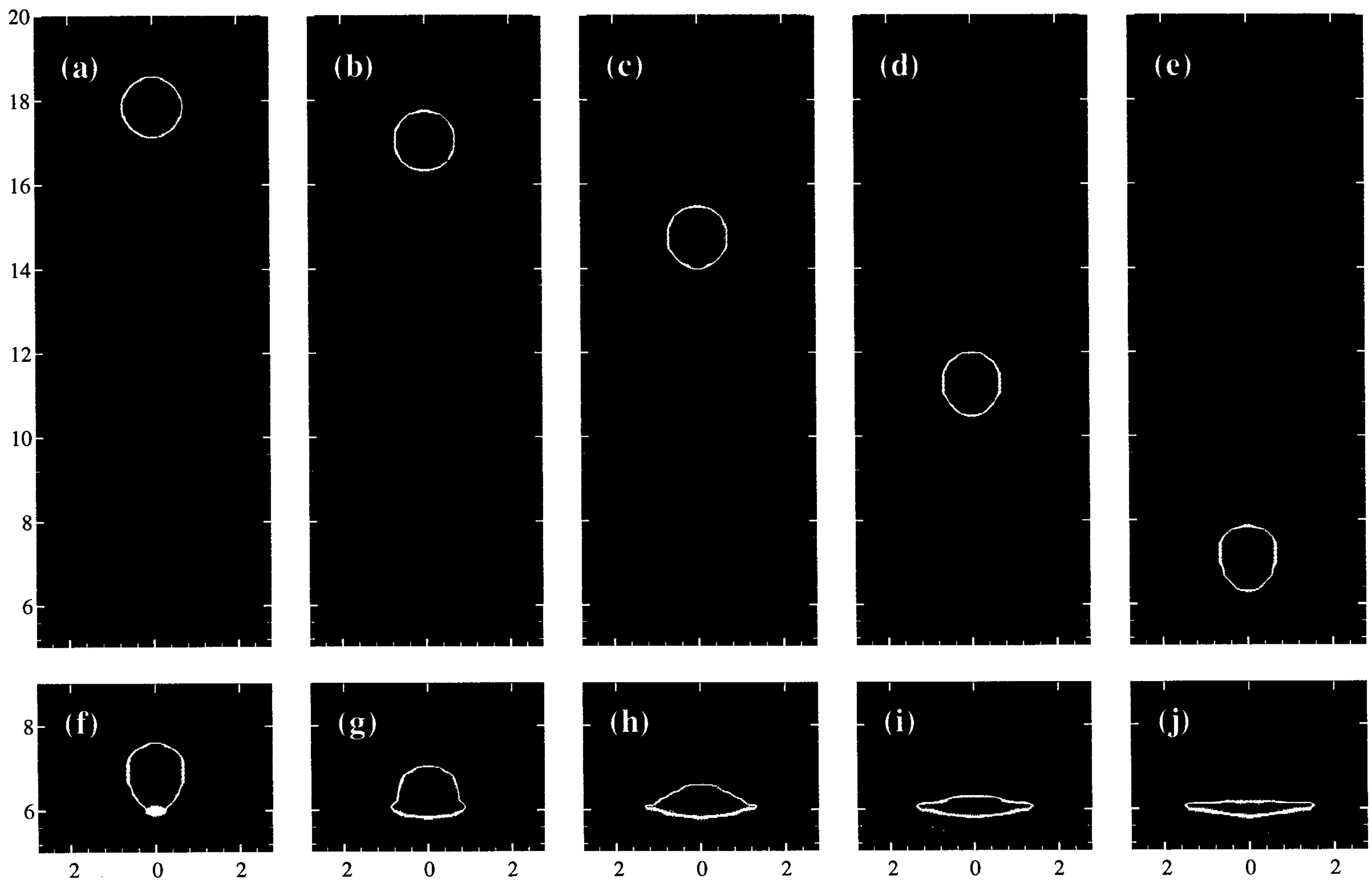

Fig. 7 A sequence of impinging process in GMAW; initial diameter is 1.5 mm, drop frequency is 14 Hz, lapsed time is 8.875 ms for frames (a) to (e), and 1 ms for frames (e) to (j).

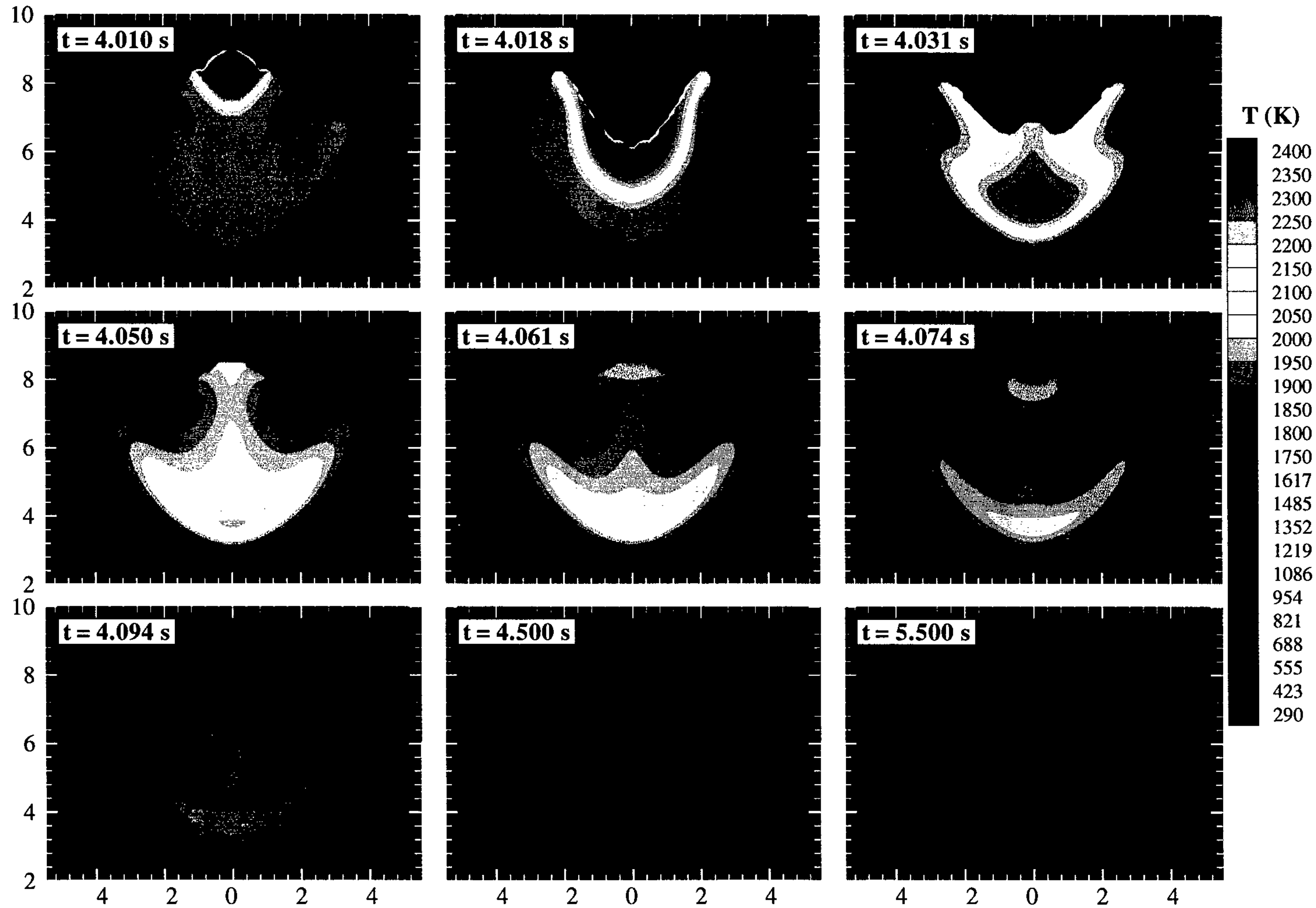

Fig. 8 Weld pool dynamics and temperature distributions at different times after the last droplet was generated and the arc was turned off at t= 4.0 s.

6. *Effects of Surface Active Elements in GMAW*

Not only in GTAW, but also in GMAW, surface active elements have significant effects on weld pool fluid flow and penetration. Figure 9 shows the weld pool shape, temperature distribution, and sulfur concentration distribution at different times when the droplet contains more sulfur (S = 300 ppm) creating a deeper penetration; as compared to Figure 10, in which the droplet contains only 150 ppm sulfur. In Figure 9, the fluid flow at the surface of the weld pool is inward (due to surface tension), carrying heat downward to create a deeper weld pool; while it is outward in Figure 10 to create a shallow weld pool. Detailed discussion can be found in Paper [7], Section IV.

7. *Effects of Droplet Size and Drop Frequency in GMAW*

For a given deposition rate in GMAW, if the droplet size is small, it requires a higher drop frequency (i.e., wire feeding rate). By comparing Figures 9, 10, 11, and 12, one can find that the major driving force for deep penetration is the surface tension force due to sulfur concentration, but not the dynamics of the droplet. The greater momentum carried by larger droplets is "damped out" by the wavy weld pool. Hence, for different droplet sizes, if they contain the same amount of sulfur, a similar weld penetration is achieved, although a little wider weld pool can be observed for larger droplets. It is noted that for smaller droplets (Figures 11 and 12), there is strong possibility that micropores can exist in the weld pool, especially under the condition when gas shielding is not adequate. Detailed discussion of the effect of droplet size on weld pool flow can be found in Paper [8], Section IV.

8. *3-D Moving GMAW*

For the first time, a 3-D mathematical model was developed to simulate a moving GMAW. Figure 13 shows a side view of the impinging process and the sulfur distribution in the weld pool. The top view of fluid flow, weld deposition height, and temperature distribution are given in Figure 14. Detailed presentations for the weld pool fluid flow, temperature, and sulfur concentration distribution as a function of time are given in Paper [9], Section IV.

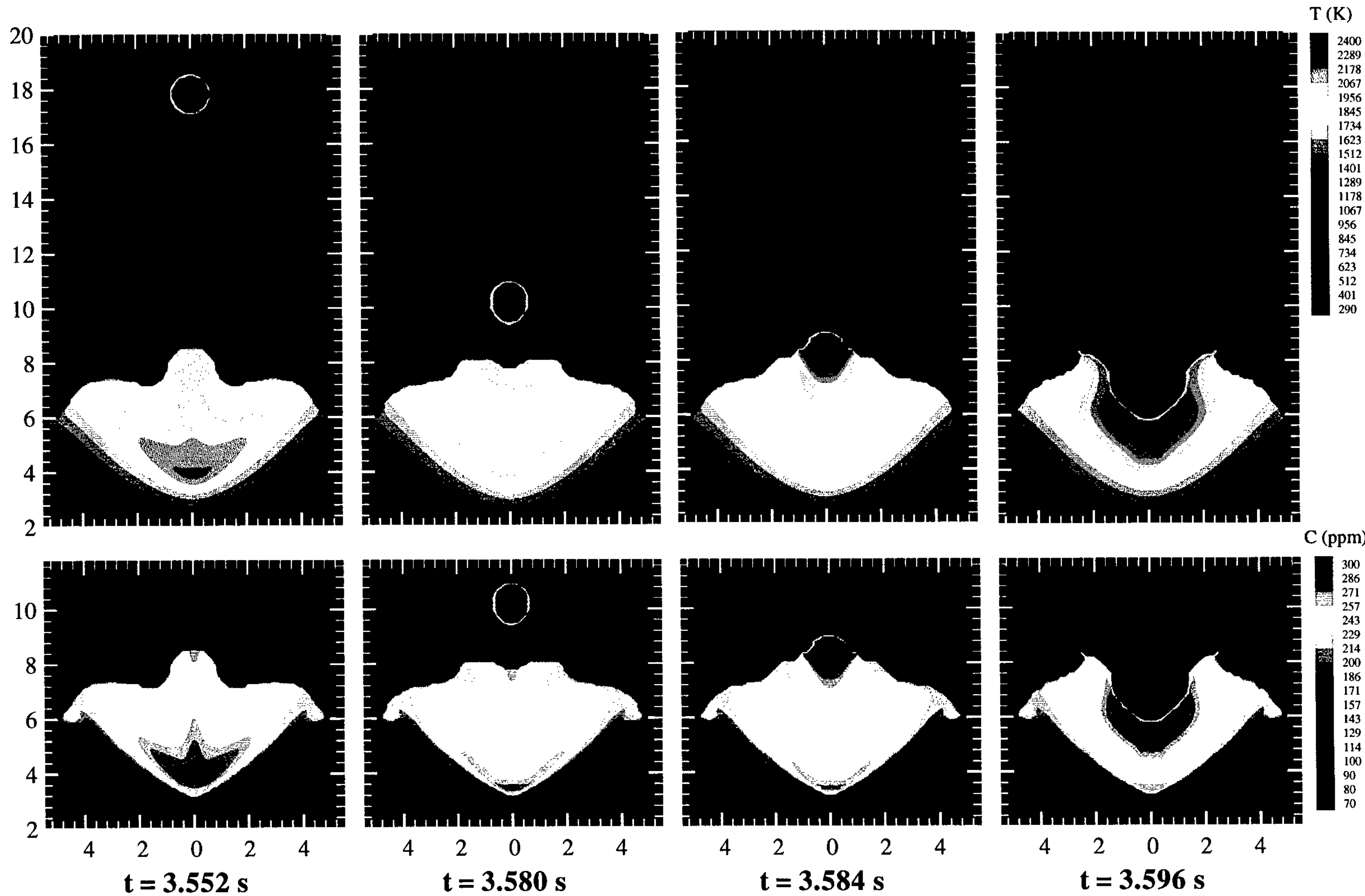

Fig. 9 Weld pool shape, temperature distribution, and sulfur concentraton distribution; droplet diameter is 1.5 mm, drop frequency is 14 Hz, and droplet sulfur concentration S = 300 ppm; base metal sulfur concentration S = 100 ppm.

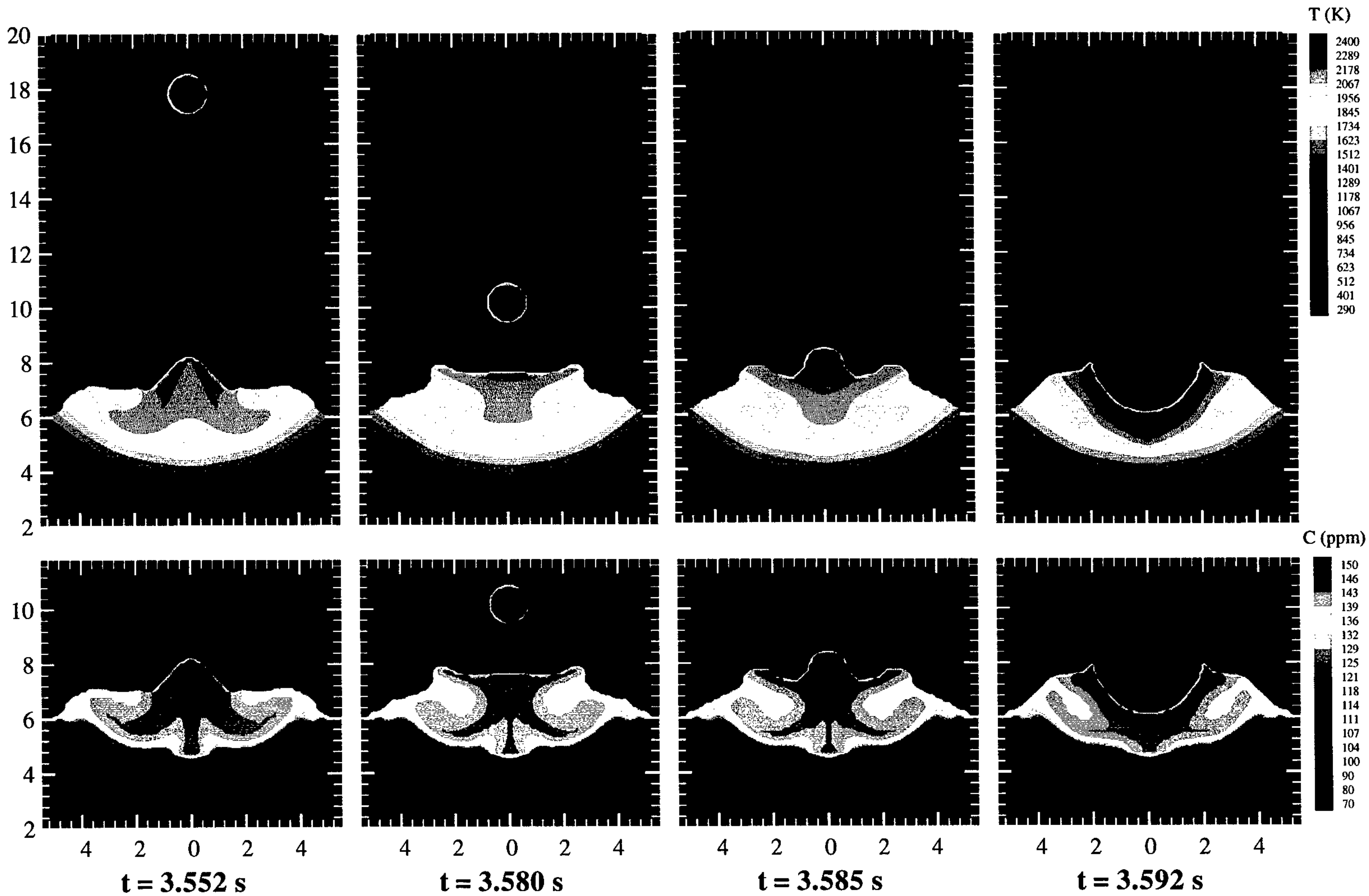

Fig. 10 Weld pool shape, temperature distribution, and sulfur concentraton distribution; droplet diameter is 1.5 mm, drop frequency is 14 Hz, and droplet sulfur concentration S = 150 ppm; base metal sulfur concentration S = 100 ppm.

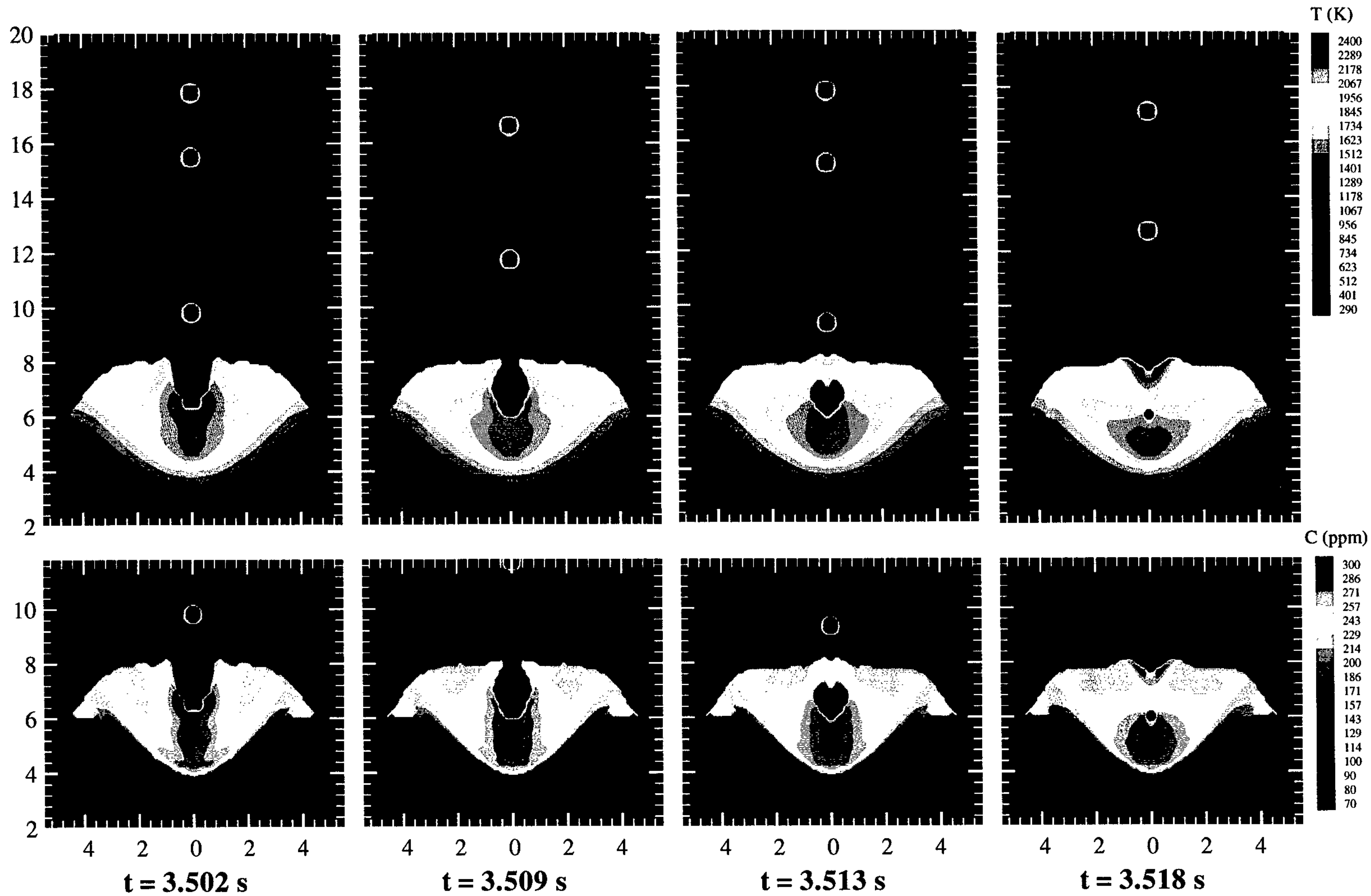

Fig. 11 Weld pool shape, temperature distribution, and sulfur concentraton distribution; droplet diameter is 0.8 mm, drop frequency is 93 Hz, and droplet sulfur concentration S = 300 ppm; base metal sulfur concentration S = 100 ppm.

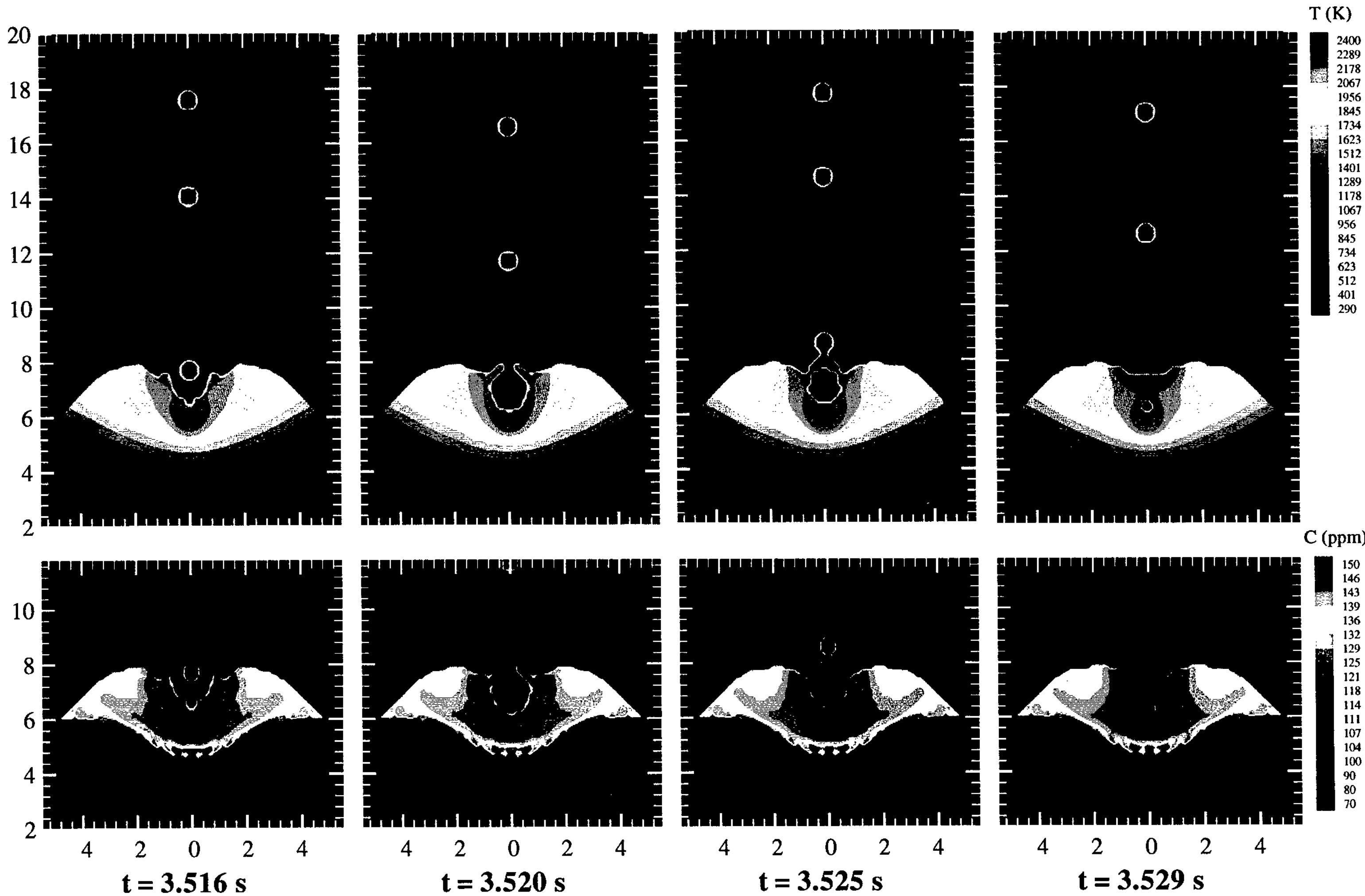

Fig. 12 Weld pool shape, temperature distribution, and sulfur concentraton distribution; droplet diameter is 0.8 mm, drop frequency is 93 Hz, and droplet sulfur concentration S = 150 ppm; base metal sulfur concentration S = 100 ppm.

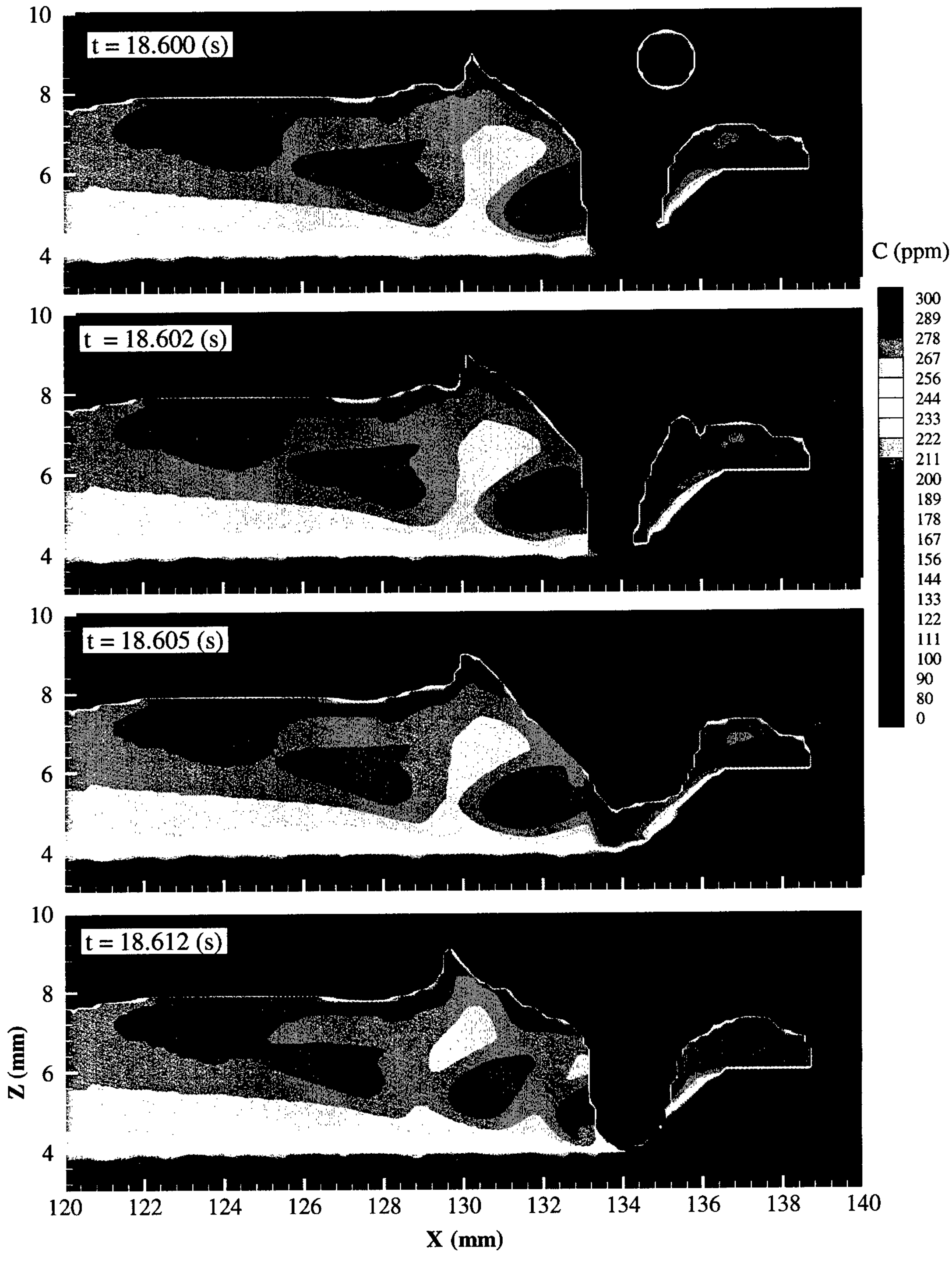

Fig. 13 The side view of impinging process and sulfur concentration distribution for a moving GMAW.

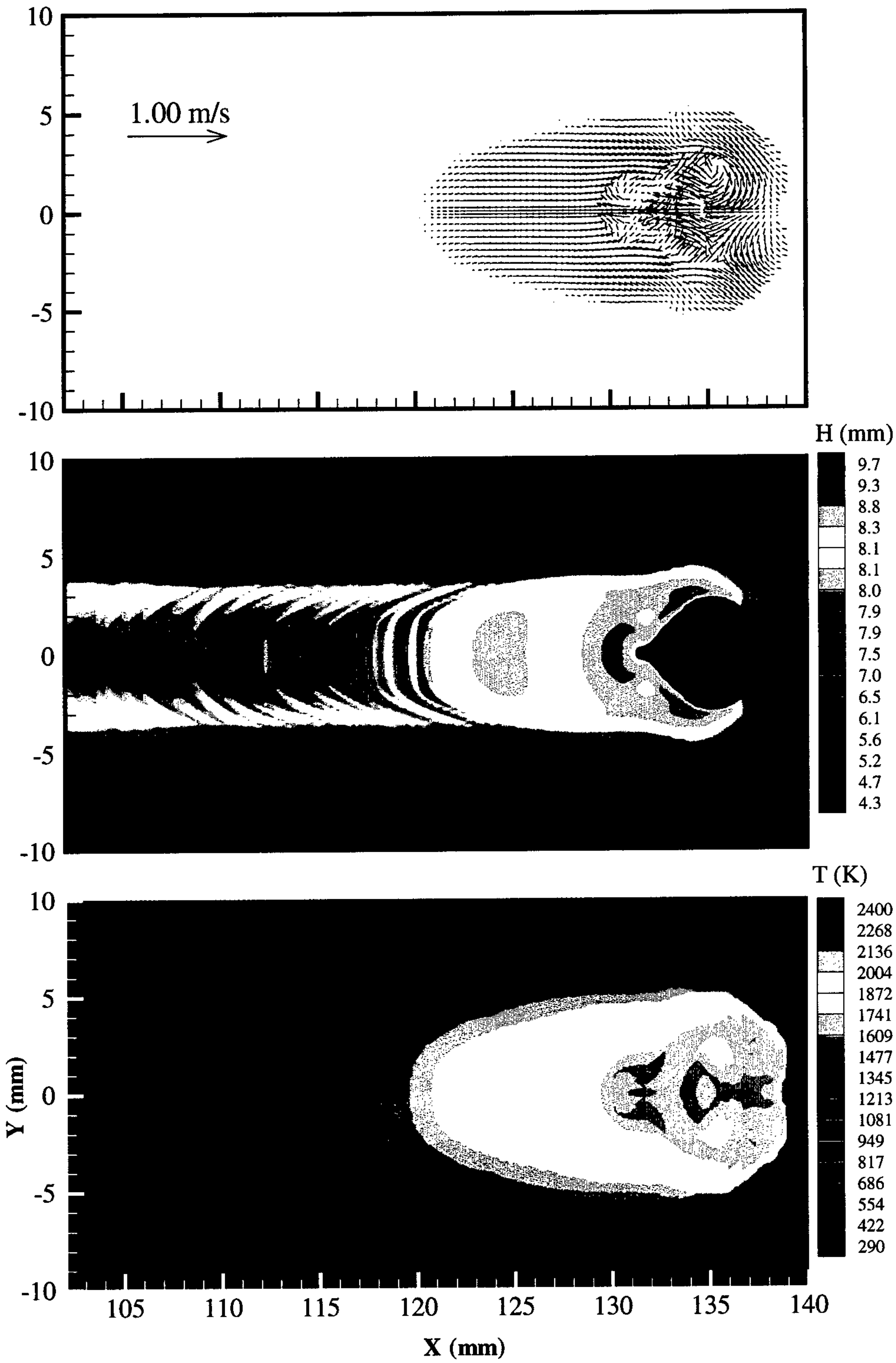

Fig. 14 The top view of weld pool fluid flow, deposition height, and temperature distribution at t = 18.611 s for a moving GMAW.

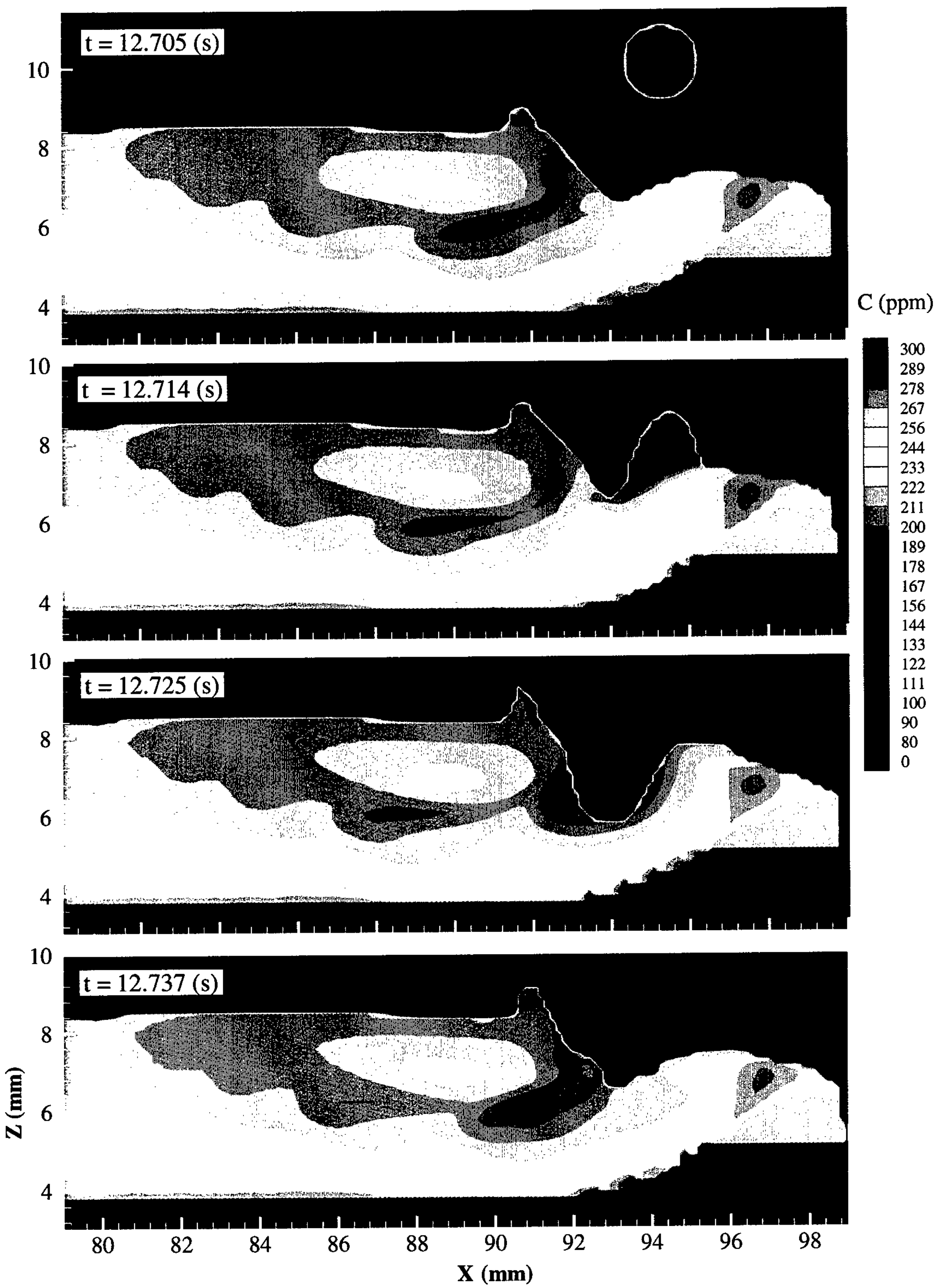

Fig. 15 The side view of impinging process and sulfur concentration distribution for a moving GMAW with preheat and groove.

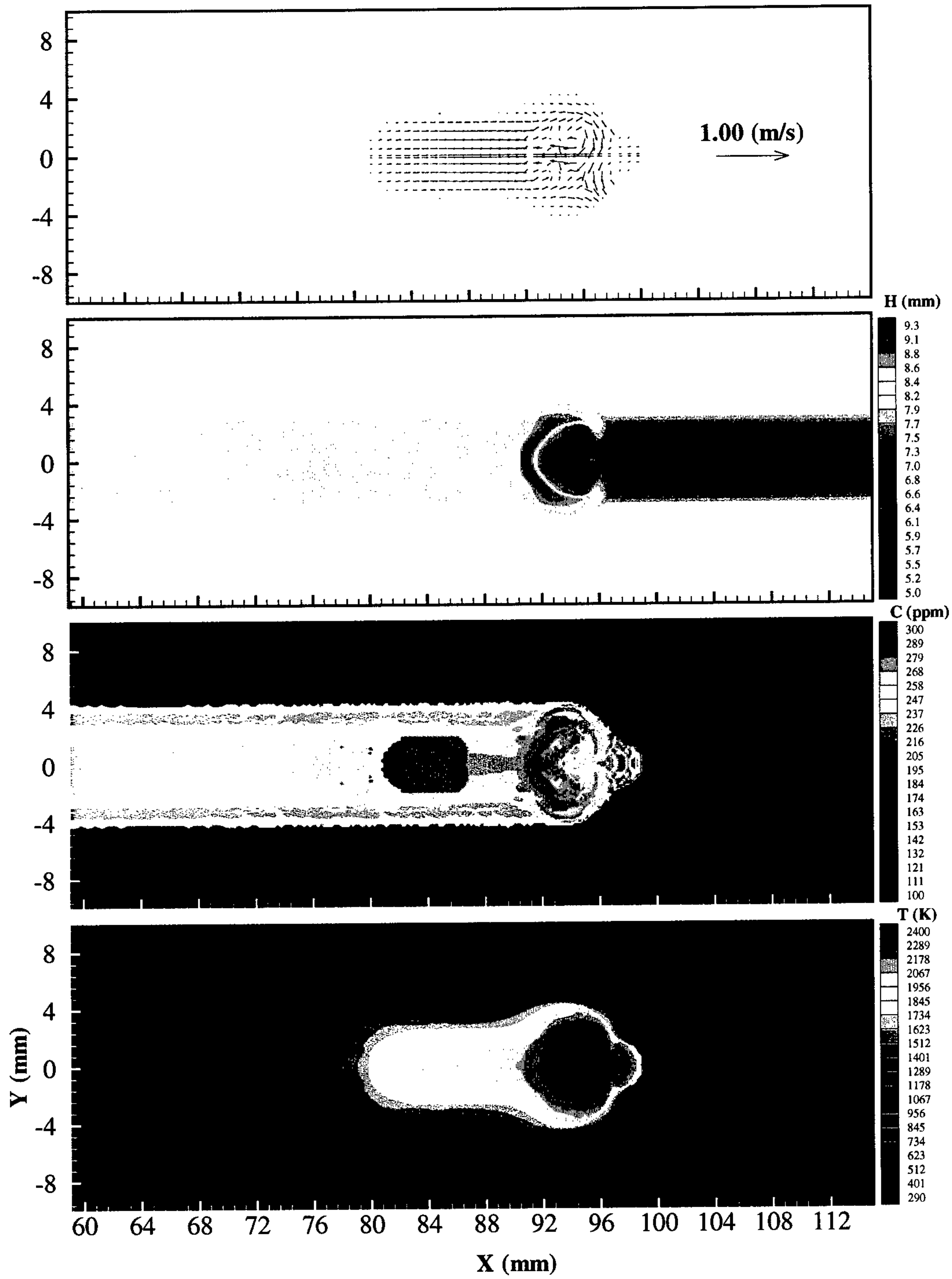

Fig. 16 The top view of weld pool fluid flow, deposition height, concentration, and temperature distribution at t = 12.737 s for a moving GMAW wiith preheat and groove.

9. *3-D Moving GMAW with Preheat and Groove*

When welding two thick metals, normally a groove is designed and preheat and/or multi-pass welding is required. Figures 15 and 16 show, respectively, the side view and top view of the fluid flow, sulfur concentration, and deposition height when there is a groove and a preheat proceeding the welding gun. Detailed discussion and results are presented in Paper [10], Section IV.

IV. List of Publications and Technical Presentations

Publications:

1. Y. Wang, Q. Shi and H. L. Tsai, "Modeling of the Effects of Surface Active Elements on Flow Patterns and Penetration Depth" (accepted for publication in *Metallurgical and Materials Transactions*).

2. Y. Wang and H. L. Tsai, "Effects of Surface Active Elements Contained in the Coating or Shielding Gas on Weld Pool Flow and Penetration" (to be submitted).

3. H. G. Fan, H. L. Tsai, and S. J. Na, "Heat Transfer and Fluid Flow in a Partially or Fully Penetrated Weld Pool in Gas Tungsten Arc Welding" (to be submitted to *Int. J. Heat Mass Transfer*).

4. H. G. Fan and H. L. Tsai, "A Unified Model for GTA Welding, Including Cathode, Arc Plasma, and Molten Pool" (to be submitted to *Metallurgical and Materials Transactions*).

5. Y. Wang and H. L. Tsai, "Impingement of Filler Droplets and Weld Pool Dynamics in Gas Metal Arc Welding" (to be submitted to *Int. J. Heat Mass Transfer*).

6. Y. P. Yang, H. L. Tsai, and X. Tian, "Modeling of Preventing Weld Hot Cracking with a Trailing Heat Sink" (to be submitted).

7. Y. Wang and H. L. Tsai, "Modeling of the Effects of Surface Active Elements on Weld Pool Flow in Gas Metal Arc Welding" (to be submitted to *Metallurgical and Materials Transactions*).

8. Y. Wang and H. L. Tsai, "Effect of Droplet Size and Drop Rate on Weld Pool Fluid Flow and Defect Formation" (to be submitted).

9. Y. Wang and H. L. Tsai, "Modeling of 3-D Moving Gas Metal Arc Welding" (to be submitted).

10. Y. Wang and H. L. Tsai, "Modeling of 3-D Moving GMAW with Preheat and Groove" (to be submitted).

Technical Presentations:

1. "Process Improvement Through Process Modeling in Welding Technologies," GM R&D Center, Warren, MI, June 3, 1996.

2. "Welding Process Modeling," Caterpillar Technical Center, Peoria, Illinois, January 9, 1997.

3. "Modeling of Heat Transfer and Fluid Flow in Welding Processes," Department of Mechanical Engineering, Arizona State University, Tempe, AZ, Sept. 5, 1997.

4. "Modeling of Transport Phenomena in Welding Processes," Department of Mechanical Engineering, University of South Carolina, Columbia, SC, Sept. 19, 1997.

5. "Current Research Efforts on both Arc and Laser Beam Welding," TRW Vehicle Safety Systems, Inc., Washington, MI, December 11, 1997.

6. "Numerical Simulation of Gas Metal Arc Welding Process," GM R&D Center, Warren, MI, December 12, 1997.

7. "Mathematical Modeling of Gas Metal Arc Welding," The Lincoln Electric Company, Cleveland, Ohio, February 17, 1998.

8. "Mathematical Modeling of Arc and Laser Beam Welding," ARL, Aberdeen, MD, March 19, 1998.

9. "Modeling of Impinging Process in Gas Metal Arc Welding," NIST, Gaithersburg, MD, March 20, 1998.

V. List of Participating Scientific Personnel

H. L. Tsai (PI)

Q. Shi (received an M.S. degree in September 1996)

Y. Wang (anticipate to receive a Ph.D. degree in September 1998)

H. G. Fan (postdoctoral fellow, partial support)

Y. P. Yang (postdoctoral fellow, partial support)

J. M. Rick (M.S., partial support)

J. A. Barnett (undergraduate, partial support)

VI. Technology Transfer to Industry

The unique modeling capabilities developed in the present study are being transferred to the General Motors Corporation through a research contract titled, "Modeling of Gas Metal Arc Welding Weld Pool in the Low Current Regime," $102,329, April 1998 – March 1999. Mr. Yun Wang, Ph.D. student who is sponsored by the project, is anticipated to complete his degree by the beginning of September 1998; then he will join GM R&D Center, Warren, Michigan. In addition, we are in the process of negotiating a research contract with Lincoln Electric, a major welding facilities manufacturer. Our modeling can help and save significant lead time for Lincoln to develop new generation of STT Waveform MIG machines.

VII. Report of Inventions

None